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VULNERABILITY ASSESSMENT OF TRADITIONAL BUILDINGS IN COIMBRA, PORTUGAL, SUPPORTED BY A GIS TOOL

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SUMMARY

The increasing concern and consequent appraisal on durability, conservation state and change of use of old buildings in urban centres is greatly related with structural safety assessment, particularly to seismic actions. It is largely recognised that the seismic vulnerability of the majority of historical city centres, with buildings without adequate seismic capacity, is high. The need to catalogue buildings according to their seismic vulnerability, particularly traditional buildings, is a key issue in any renewal or rehabilitation process. Recently, different methods for seismic vulnerability assessment have been proposed, with different levels of detail. Research carried out on seismic vulnerability have underlined that the performance of traditional buildings under earthquake actions is governed by several structural features, some of which can be peculiar of each urban context and construction technology. Seismic vulnerability assessment extended to whole historic centres has outlined the importance of GIS mapping applications in order to aid in the intervention and risk management plans. The need for an integrated multi-purpose tool, connected with a GIS, as well as with a relational database, in order to have a deeper and interdisciplinary knowledge of the site and hence to be able to create a modular approach and manage the historical building stock, conservation works, retrofitting strategy, risk assessment, building characteristics and vulnerability, damage and cost estimation is essential. In this paper, it is presented and discussed the strategy and methodology adopted for the vulnerability assessment of the city centre of Coimbra, in Portugal, through the GIS mapping of the building stock of the project perimeter. Development of vulnerability studies in urban centres can be conducted aiming to identify building fragilities and to reduce the seismic risk.

1. INTRODUCTION

Since the early 70´s renovation programs of old city centres became a significant scope of political and research activities, as the consequence of the increasing concern on urban sustainability and its rising public promotion given by international treaties and research development on this matter. Various sub-topics included in the renovation processes are currently being treated, such as territorial planning issues, refurbishment measures for buildings, health and living conditions, decree-law on house rents, energy sustainability, and architectural authenticity. But, an evaluation program of the structural safety and vulnerability for old buildings is not yet incorporated as a true concern in local city council projects or national building policies.

Introducing simplified methods with the intent to evaluate the seismic capacity of old masonry buildings that where built without concerning the earthquake-resistant demand, representing the majority of buildings in old city centres. These must de categorized by criteria driven definition to guide intervention priorities, susceptible

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to be applied to our national historical building stock. When analysing an urban area in respect to the historical preservation of buildings, the common concern of intervening with the goal to guarantee minimum safety requirements is not always shared by most of the citizens, especially by the building owners, but not even by technicians and authorities. Therefore, many are the strategies and methods to systematize various tasks in a historical area put up for preservation, which effectiveness depends mainly on the type of buildings (structural schemes and techniques, construction materials), on the type of global project approach (singular building, group of buildings, urban intervention zones , etc.) and on the precise final purpose (risk assessment and strengthening decision, future rehabilitation projects, definition of a council maintenance policy, etc.).

Recently, in Portugal, new legal guidelines have been approved to create the SRU´s – Urban Rehabilitation Societies. These new societies will be implemented as a type of "neighbourhood councils" or "enterprise-city blocks" and they will be responsible, within the rehabilitation process, for defining and planning strategies, promoting and executing renovation actions. These societies are composed by city council housing department, owners, design engineers and architects, public and private investors and representatives of tenants. This political and administrative tool will sure help urban renewal and renovation, hoping that their will be a clear and noted concern not only on social and architectural areas but also on structural safety improvement.

In spite of all of this, the seismic risk for the resident population in old city centres and buildings should not be overlooked. In Coimbra, if an earthquake event occurs, the very peculiar characteristics of the narrow street net, in which buildings are confronted, in the worst scenario will not allow the passage of civil protection forces and possible support for victims.

2. VULNERABILITY OF OLD CITY CENTRES

Seismic vulnerability is an intrinsic property of the building structure, a characteristic of its own behaviour to seismic action described by a cause–effect relationship, in which the earthquake is the cause and the effect is the damage suffered. The seismic vulnerability assessment of existing structures, infrastructures, special and essential buildings, nuclear facilities, among others, have attained an advanced level of study due to the accumulated investigation work carried out during the past 30 years. There are different methods of seismic vulnerability evaluation, with different levels of detail, which have been adopted in several vulnerability studies throughout the world [CNR, 1999], [INGV-GNDT, 2001]. However, in many countries, little has been done to reduce the seismic vulnerability of the older buildings of historical city centres that probably when subjected to an earthquake of moderate to high intensity, will certainly result in severe damages at various levels: physical, social and economical, but also losses of human lives.

Structural vulnerability analysis in old city centres, urges to be taken to a higher stake in Portugal. Development of vulnerability studies in urban centres should not be exclusively conducted for structural aspects, but the non-structural, functional and operative should also be considered [Giuffrè, 1993], so that they can provide useful information in risk reduction and territorial planning. In another sense, the vulnerability assessment constitutes an important tool in the support to decision making related with the rehabilitation, strengthening or at the worst demolition of buildings, location of life-services, etc.

The occurrence of an earthquake is always associated to socio-economical costs with human impact and very significant material waste. However, the losses in terms of cultural, heritage and architectural values are particularly unrecoverable. The evaluation of the seismic safety of historical buildings (churches, monuments, etc.) has motivated the vulnerability assessment of these type of constructions and quickly extended to the other type of buildings, such as common residential type (see figure 1). The building heritage of the historical city centres have suffered considerable damage in recent earthquakes, pointing out their reduced capacity to resist to horizontal actions. In spite of this, the knowledge on strengthening and improvement strategies of old buildings, prevention activity and surveys needs, has to be discussed as a national target, or a regional responsibility and concern.

Taking into account that the majority of old buildings in old city centres are load-bearing masonry structures, the cataloguing of the common masonries is fundamental, to register their physical characteristics, mechanical and strength properties, such as; Young modulus, shear and compression strength, behaviour under cyclic loading and typical collapse mechanisms. Numerical models can be valuable tools in any level of evaluation of the seismic vulnerability. Any vulnerability assessment methodology should be adapted to the local construction techniques, as well as materials and constructive solutions, to account for particularities of the regional construction.

Figure 1: Aerial views of the old city centre of Coimbra

3. TRADITIONAL BUILDING STOCK AND CONSTRUCTION DETAILS

Architectural typology and traditional construction techniques in the old city centre of Coimbra are variable in function of several parameters as, for example, the dimension and nobleness of buildings. In respect to housing buildings, very simple structural schemes are observed: load-bearing external stone masonry walls and wooden floor slabs (see figure 2). For the majority of buildings that have been inspected, it was observed the systematic use of wood, in structural elements of floor slabs, roofing structures and floor coverings [Vicente et al, 2005]. Limestone elements were mainly used in external load-bearing walls, surging other materials less applied, such as solid or perforated clay bricks. The use of river sand in mortars for bed joints and external renderings is also very common. In most cases, roofs are covered with clay tiling of various dimensions, colours and formats. Interior partition walls are thin and sometimes suffer warping, revealing, in some cases, of structural movement, as consequence of creep and aging phenomena. Staircases have, typically, high slopes and are composed by materials with high fire vulnerability, which makes difficult emergency evacuation in the case of fire incident.

Irregular masonry fabric

Wood roof and floor structure

Figure 2: Construction details of the traditional old masonry buildings

The majority of buildings are normally in bands with strait and windy accesses, constituting another negative fire safety factor. Typically, these building have no basement, since a large area of this part of the historical centre of the town is quite close to the river (downtown), on a flat surface land (in opposition to the high historical centre - not included in this study - that covers the mountain-side, enveloping the old University, erected on the top of the hill).

4. GIS MAPPING

Risk management of historical towns in many cases is undertaken without a general planning tool. A first consequence of this is that technicians and decision makers (city councils or regional authorities) do not have a global view of the site area where they must operate and this can lead to inadequate decisions as far as what concerns rehabilitation and refurbishment policies. Therefore, it is highly recognized the advantages of an integrated multi-purpose tool, connected with a GIS [ArcGis, 2005], as well as with a relational database, in order to have a deeper and interdisciplinary knowledge of the site and hence to be able to manage the historical building stock, conservation works, risk assessment, building vulnerability, damage and cost estimation.

The use of a data-base associated to a GIS environment represents a powerful tool for seismic risk evaluation. In this study, which envolves a large scale building vulnerability evaluation and damage estimation, the GIS application is a valuable analysis method, since the databases associated can be periodically updated, allowing the mapping of different damage scenarios, risk reduction actions associated to strengthening strategies.

The software used for the GIS is connected with a relational data base on structural building characteristics that governs the structural behaviour of historic buildings, with particular focus on their seismic vulnerability. Several aspects characterizing any urban area, which are at present stored and managed, require the use of GIS in order to achieve an organic view of the inter-connected problems concerning the given area. GIS tools are used to provide good global overview of building quality, current conservation status, risk scenarios and potential damage mapping for different seismic intensities.

DB Managing System **GIS Application**

Figure 3: Database and GIS framework

5. VULNERABILTY ASSESMENT PROCEDURE

The methodology used to evaluate the vulnerability of the historical city centre of Coimbra is considered an indirect method, chosen normally for urban scale analysis, due to the number of buildings to classify. The formulation proposed is based on the GNDT methodology [GNDT, 1994] for the vulnerability assessment of residential masonry buildings, used over the last 20 years, which was adapted to the particular Portuguese masonry buildings, improved, and extensively applied in the case study of Coimbra.

All information used in the vulnerability assessment was preceded by the appraisal, diagnosis and inspection actions, gathering information on the buildings by fieldwork using a detailed check-list, through an extensive survey of all building stock of the old city centre [Vicente et al, 2005a]. Presently 771 buildings that constitute the project perimeter have been surveyed and over 325 of them have classified and evaluated in respect to their of seismic vulnerability.

The method is based on the calculation of a vulnerability index, as the weighed sum of 13 parameters. These parameters are related to 4 classes of growing vulnerability: A, B, C and D. Each parameter evaluates an aspect influencing the building response and is chosen the vulnerability class associated to it. A weight 'p_i' is assigned to each vulnerability parameter, ranging from 0.25 for the less important parameters in terms of vulnerability, up to 1.5 for the most important ones (e.g. conventional strength) as shown in table1. This weight that is attributed to each one of the 13 parameters is function of its influence on the global seismic vulnerability of the structure. The vulnerability index ranges between 0 and 575, but the value obtained by the weighted sum can be normalized within the range of variation $0 < I_v < 100$ and it is defined as the vulnerability index or score. The vulnerability index calculated can be used to estimate the building damage under a specified seismic level action, as will be shown.

In table 1 are shown the 13 parameters used in the formulation of the seismic vulnerability index.

Table 1: Vulnerability index (Iv)

	PARAMETERS	**Class C_{vi}**				**Weight**
		A	**B**	**C**	**D**	**p_i**
1	Type of resisting system	0	5	20	50	1.00
2	Quality of the resisting system	0	5	20	50	1.00
3	Conventional strength	0	5	20	50	1.50
4	Maximum distance between walls	0	5	20	50	0.75
5	Location and soil conditions	0	5	20	50	0.75
6	Position and interaction	0	5	20	50	1.50
7	Plan configuration	0	5	20	50	0.75
8	Regularity in height	0	5	20	50	0.75
9	Wall openings and alignments	0	5	20	50	0.50
10	Horizontal diaphragms	0	5	20	50	1.00
11	Roof system	0	5	20	50	1.00
12	Fragility and conservation state	0	5	20	50	0.75
13	Non-structural elements	0	5	20	50	0.25

VULNERABILITY INDEX
$I_v = \sum_{i=1}^{11} C_{vi} p_i$
$0 \leq I_v \leq 575$
Normalized index => $0 \leq I_v \leq 100$

From the vulnerability analysis that was carried out, evidences a average vulnerability index of 48.09. For about 83% of the building stock it was calculated a vulnerability index over 40, and 44% over 50 (see figure 4b). This first level evaluation, even though limited, is fundamental not only for the 13 parameter evaluation (masonry quality, state of conservation, structural irregularities, building interaction, etc.) but essentially for the identification of the most critical and vulnerable buildings, and that are suggested for a more detailed analysis in terms of seismic vulnerability [Vicente et al, 2006]. Only 15% of the buildings have a I_v below 40, which figures as the lower limit for vulnerability allowed.

From all parameters evaluated, the most variable are parameters 4, 6, 8, 9 and 13 (see figure 4a and 4c). From all parameters evaluated, the most influent are parameters 1, 3, 6, 8 and 10 (see figure 4a and table 1) since their weights range between 1 and 1.5. If any strengthening action is to be taken it should be guided by the improvement and homogeneity of the vulnerability classes of these parameters.

The typical traditional limestone masonry buildings of the city centre of Coimbra are best represented if evaluated through a weighted average of the assessed building types. In this case the mean vulnerability index (I_v=48.09) corresponds to the EMS building typologies and vulnerability classes by adjusting the construction description. Table 2 shows the correspondence between various vulnerability classes and calculated values.

Table 3: Correlation between the damage grade and damage index

Iv – Vulnerability index	EMS 98 Class	EMS 98 Typology	V-Macroseismic method vulnerability index
48.09	B (most probable)	Field stone – M1 Simple stone – M3	0.796

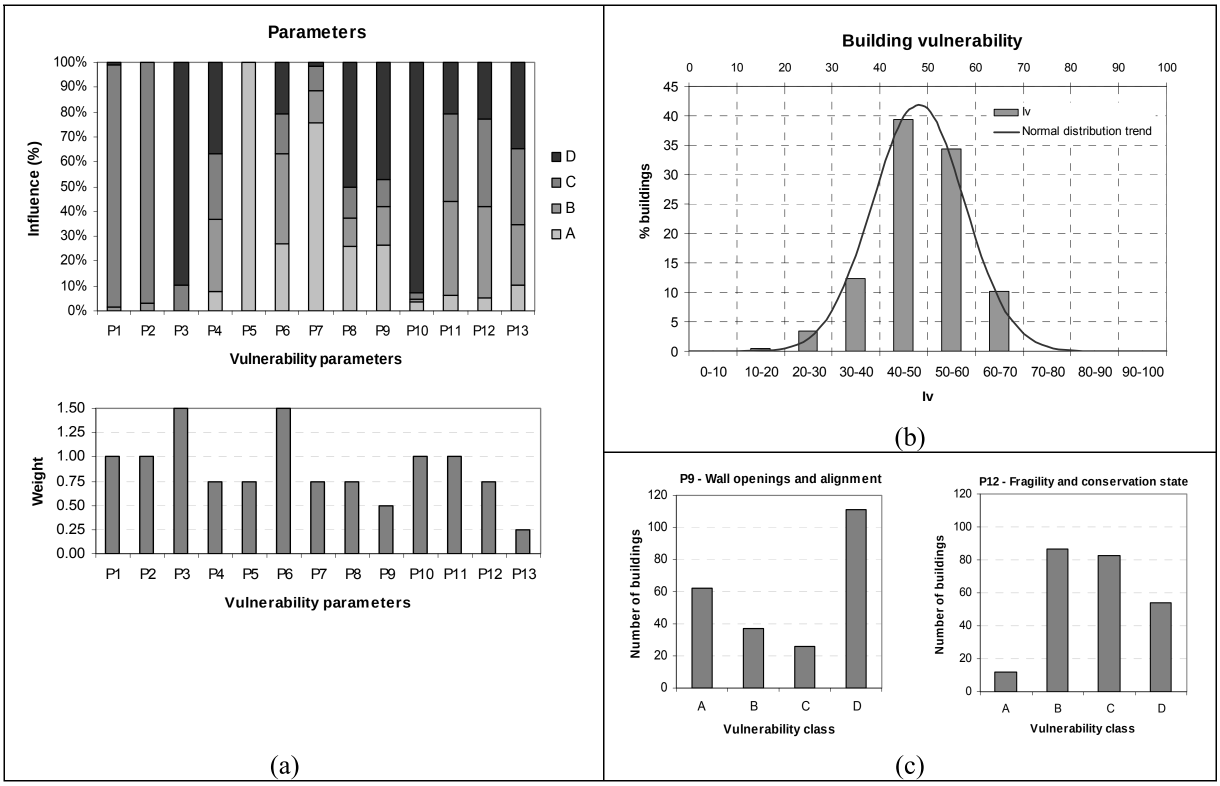

Figure 4: Vulnerability assessment results

Figure 5: Vulnerability index analysis

6. DAMAGE SCENARIOS

The evaluation of physical damage through seismic risk scenarios was carried out using two different approaches. The vulnerability curves of Petrini & Benedetti [Benedetti, 1994] providing the damage index that expresses the damage, d, in a normalized scale ($0 \le d \le 1$) defined as the ratio between repair cost and reconstruction cost (the latter corresponds to the value of the building). High damage values (0.8 to 1.0) are considered as equivalent to building collapse.

The other approach to the damage estimation was based on the Giovinazzi formulation [Giovinazzi and Lagomarsino, 2004] proposed analytical function (equation 1), for masonry buildings, derived from the vulnerability curves obtained by the completion of the EMS 98 vulnerability model. This expression is very similar to the function proposed by [Sandi and Floricel, 1995].

$$\mu_D = \left[1 + \tanh\left(\frac{I + 6.25 \times V \text{ -}13.1}{2.3}\right)\right] \quad 0 \le \mu_D \le 5 \tag{1}$$

The mean damage grade calculated depends on the vulnerability index, V, ranging from 0 to 1 and the macroseismic intensity, I (EMS) [Grunthal, 1998]. Equation 1, can also be used for the vulnerability index calculated through the methodology explained in section 5, transforming the vulnerability index, I_v, into the macroseismic method vulnerability index, V, through equation 2.

$$I_v = 156.25 \times V - 76.25 \tag{2}$$

The correlation presently accepted [Bramerini et al, 1995] between the damage grades and the damage index is indicated in table 3.

Table 3: Correlation between the damage grade and damage index

Damage grade, D_k	0	1	2	3	4	5
Damage index, d	0	0.01	0.1	0.35	0.75	1

The vulnerability curves for the mean damage values given by the damage index and damage grade for the whole old city centre and for the 5% and 95% quartiles, are represented in figure 6a and 6b, respectively.

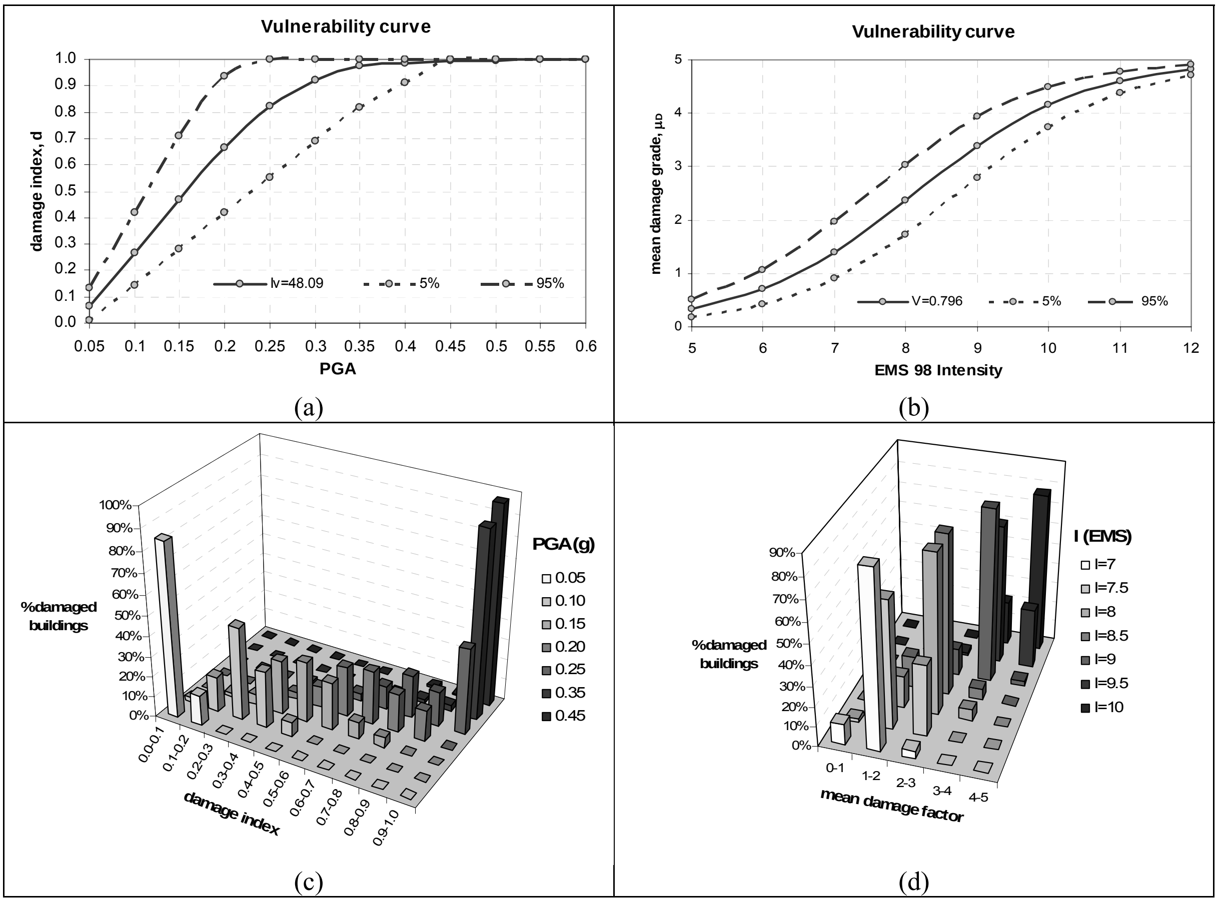

Figure 6: Vulnerability curves and damage distribution for both damage estimation approaches

Figures 6c and 6d represent the damage histograms for several seismic input intensities and for both approaches. In figure 7, it can be observed the damage distribution throughout the old city centre for different seismic actions using the SIG application, for PGA values in terms of damage index and for macroseimic intensities for mean damage grades. In order to compare damage index and the mean damage grade, the peak ground acceleration can be related to the macroseismic intensity, using the I-a_g Guagenti and Petrini law, [Guagenti and Petrini, 1989]:

$$\ln(PGA) = 0.602 \times I - 7.073 \tag{3}$$

By observing figure 7, the obtained seismic risk scenario, it can be seen that the expected damage for a seismic intensity of 9 (corresponding to a_g=0.20g) is very high. Over 75% of the masonry buildings present damage between 3-4, equivalent to damage states between heavy and very heavy.

Figure 7: Damage scenarios for both approaches

To the damage distribution histograms obtained for both approaches and taking into account the damage intervals used, the distribution parameters, mean value and variance were treated statistically and originated discrete probability functions. The damage data was fitted to a binomial and beta distribution (see equation 3 and 4), as shown in figure 8.

$$PMF: p_k = \frac{n!}{k!(n-k)!} \times d^k \times (1-d)^{n-k} \quad n \geq 0; \quad 0 \leq p \leq 1 \tag{4}$$

$$PDF: \quad f(x,\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\times\Gamma(\beta)} \times \frac{(x-a)^{\alpha-1} \times (b-x)^{\beta-1}}{(b-a)^{\alpha+\beta-1}} \quad a \leq x \leq b; \quad \alpha,\beta > 0 \tag{5}$$

The probability mass function of the binomial distribution depends only on the mean value of the damage histogram. This value was taken as the mean damage index, d_m, and mean damage grade, μ_D, as shown in figure 8.

For the probability density function of the beta distribution, α and β are parameters of the distribution and Γ, is the gamma function. The studies of [Giovinazzi, 2005] have shown that the beta distribution is the most versatile, through controlling the shape of the distribution, by the parameters t and r, allowing to fit very narrow or broad damage distributions.

It can be observed the dispersion of the binomial distribution, as already stated by other authors in other damage and risk scenarios studies which is very dependent on the building type analyzed. The beta distribution seems to be adjusted very well to the damage data, as shown in figure 8. Nevertheless other probability density functions are also adjustable, such as the lognormal and chi-squared taking into account their renormalization.

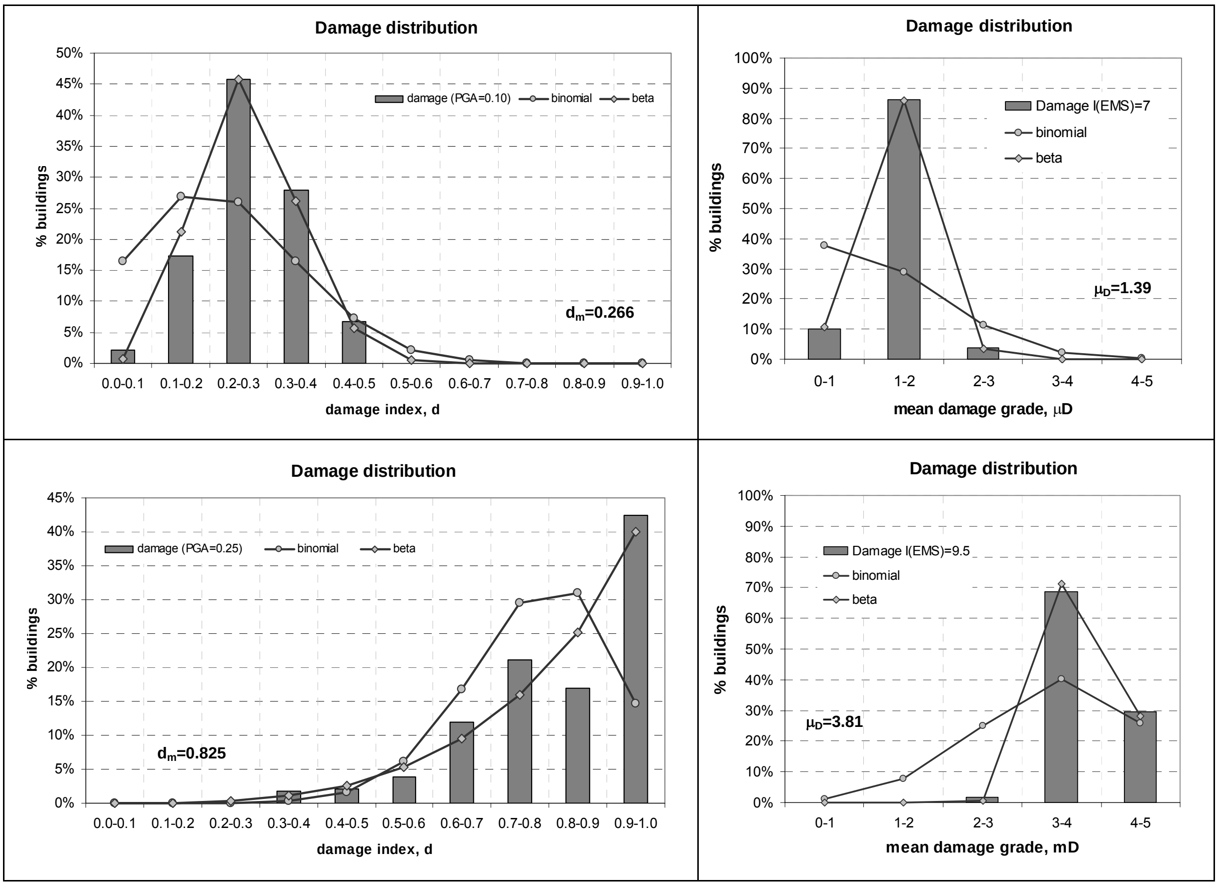

Figure 8: Estimated damage distributions

Based on this statistical damage evaluation, it can be defined DPM (damage probability matrices) for the traditional masonry buildings in Coimbra. These matrices will provide an expected damage distribution for a certain damage level and the best data interpolation probability density functions

7. CONCLUSIONS

The vulnerability assessment method development has revealed to be very exhaustive in analysis of the building constructive characteristics. The vulnerability assessed is therefore of good reliability and consequently the results produced from the use of the vulnerability scores. The seismic vulnerability of the old city centre Coimbra is relatively high and in light to this, optimized interventions for improving seismic response and conservation of old buildings assisted with mechanical and mathematical modelling are needed in the mitigation of seismic risk.

The evolution of the urban building stock has proven to be complex and weakness revealing when taking into consideration the diachronic process of building in old and historical city centres (weak connections, widening or building sharing walls). Therefore, seismic vulnerability of building aggregates and façade walls should also be analysed, other than the single building approach. Presently, it is being developed and applied analogous vulnerability index for building aggregates and wall façades. This vulnerability assessment method and risk scenario mapping intends to be applicable for other regions and old city centres, and if needed easily adapted and slightly modified for specific building features.

For the damage scenarios studied, the results attained are very well correlated with the building constructive features and fragilities of the built-up environment. Even though the city of Coimbra is inserted in a low to moderate hazard region, the high seismic building vulnerability brings up the considerable global seismic risk of the building stock.

The SIG application and DB managing system enable to store building features and survey information, assess seismic vulnerability, as well as, damage and risk scenario prediction, allowing data upgrading and improvement for the historical city centre. This integrated tool is essential in various activities, such as the development of strengthening strategies plans, cost-benefit analysis, civil protection and emergency planning [RISK-UE Project].

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